

A thought experiment with clocks in static gravity

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Abstract

In order to directly demonstrate that in static gravitational field the rate of clocks increases with their distance from the source a simple thought experiment is proposed.

1 Introduction

The redshift of the frequency of photons as they travel upwards in a static gravitational field and corresponding increase of the frequency of clocks (e.g. of the spacings between atomic levels) were theoretically discovered by Einstein long before he constructed general relativity. These phenomena are discussed in a vast literature going from monographs on general relativity to popular books. In the recent articles [1, 2, 3] it has been argued that in a static field for a static observer the frequency of the photon does not change and that it is redshifted only with respect to the blueshifted atomic (nuclear) levels. Strangely enough, this statement met with objections from some of the experts in general relativity. These requested from the authors a thought experiment involving only clocks but no photons, which could prove that standard clocks are running faster when they are raised above the ground. The present note proposes such a thought experiment. In order to make the *pro* and *contra* arguments clearer the following text is written as a dialogue between a professional relativist (R) and the author (A).

2 Dialogue on the thought experiment

A: In refs. [1] - [3] two kinds of arguments were presented: theoretical and experimental. According to the theoretical argument, the wave solution of Maxwell's equations in a static gravitational field must have a fixed frequency equal to that of the e.m. source since the coefficients of Maxwell's equations do in that case not depend on time.

R: The conservation of energy (or frequency) of the photon depends on the definition, depends on what you choose to call the energy or frequency, on the definition of time and the system of reference. To be operationally meaningful you have to specify the way of measuring these entities.

A: As we consider a static gravitational field we should choose observers which are at rest in that field, say in laboratories situated at ground floor and the upper floor of the same building. That was how the first measurements of gravitational redshift were performed in the famous experiments of Pound and Rebka forty years ago. We should not consider observers in moving elevators. To them the gravitational field is not static. Moreover in a falling elevator the gravitational field vanishes locally.

R: OK. Let choose the static observers and consider the experiments by Pound et al. In these experiments photons were emitted by excited iron nuclei at the ground floor and their absorption by iron nuclei in their ground state was measured at the top of Harvard tower. It was observed that the energy of photons was not sufficient to excite in the iron nuclei upstairs the same level from which they were emitted downstairs. The relative shift of the frequency of photons and nuclei was $-gh/c^2$, where h is the height of the tower, $g = 10\text{m/s}^2$ and c – the velocity of light. One can interpret the experiment by saying (as the authors of [1] - [3] did) that the energy of the photon has not changed, but that the energy of excitation of iron nuclei (the rate of the clock) has fractionally increased by $+gh/c^2$.

Alternatively, there is an equally valid viewpoint according to which the clock rates are the same while the photon frequency is different. For that it is enough to consider local inertial frames momentarily at rest at the world-points of the emission and absorption of the photon.

A: But neither Pound, no his coworkers (thank God!) used in their experiments falling elevators.

R: One can introduce local time by simply assuming that standard clocks do not change their rate with their height. Anyway, you are attempting improperly to subdivide the gravitational redshift phenomenon into two sep-

arate processes, that separately have no operational meaning. The only operationally meaningful statement is that when a photon is emitted at the bottom of the tower its frequency as measured by the identical clock at the top of the tower is lower. You cannot determine whether it was the photon or the clocks that were responsible for the shift.

My view would be different if you could carry out the following thought experiment. Two identical clocks are placed one at the top of a tower, the other at the bottom. Demonstrate without connecting the clocks by photons and otherwise disturbing the clocks that the top clock runs faster than the bottom clock by the standard gravitational shift. This would be a demonstration of your assertion that the photon frequency does not change. I believe such a demonstration to be impossible.

A: There were special experiments described in refs. [1], [2] in which one of two clocks travelled on an aircraft and then was brought back to another one which was all this time at rest in the laboratory. These experiments showed that in agreement with general relativity the clock which travelled (after taking account of special relativity twin effect) was ahead of that which was at rest.

R: These results do not change my point of view, because the two clocks, in the course of the experiment, were treated differently: one made a loop in space, while the other was not moved at all. Thus, those experiments demonstrate actually only that the total elapsed times differ and say nothing (except by inference) about the instantaneous difference in their rates.

A: Inference is an inalienable part of physics. But I shall not dwell on this here. I shall just propose that thought experiment about which you asserted “I believe such a demonstration to be impossible”.

Consider two rooms: one at the ground floor, the other at the top floor of a building. One starts with two identical standard clocks at the bottom room. At a certain moment one raises the first clock to the room upstairs. After some time T one raises the second clock in the same way and compares the time it shows with that of the first clock. If general relativity is correct, their time difference should be $\Delta T = (gh/c^2)T$. In this thought experiment both clocks are treated absolutely identically. Nevertheless the first clock will be ahead of the second. As time is uniform and both clocks are not moved during the time T , this thought experiment yields the instantaneous difference in the rates of the clocks, which is of course equal to $\Delta T/T = gh/c^2$.

3 Conclusion

By a thought experiment (which with improvements in the precision of atomic clocks could one day become a real one) it is shown that when measuring the “gravitational redshift of photons” one actually measures the gravitational blueshift of clocks.

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References

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